Renewable and Sustainable Energy Reviews 41 (2015) 85–98

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Heating and cooling energy trends and drivers in buildings

Diana Ürge-Vorsatz [a,1], Luisa F. Cabeza [b,*], Susana Serrano [b], Camila Barreneche [b], Ksenia Petrichenko [a]

[a] *Center for Climate Change and Sustainable Energy Policy (3CSEP), Department of Environmental Sciences and Policy, Central European University (CEU), Nádor utca 9, 1051 Budapest, Hungary*
[b] *GREA Innovació Concurrent, Universitat de Lleida, Edifici CREA, Pere de Cabrera s/n, 25001 Lleida, Spain*

A R T I C L E I N F O

Article history:
Received 7 June 2014
Received in revised form
2 August 2014
Accepted 16 August 2014

Keywords:
Buildings
Thermal energy use
Drivers
Trends
Global basis
Regional basis

A B S T R A C T

The purpose of this paper is to provide a source of information on thermal energy use in buildings, its drivers, and their past, present and future trends on a global and regional basis. Energy use in buildings forms a large part of global and regional energy demand. The importance of heating and cooling in total building energy use is very diverse with this share varying between 18% and 73%. Biomass is still far the dominant fuel when a global picture is considered; the role of electricity is substantially growing, and the direct use of coal is disappearing from this sector, largely replaced by electricity and natural gas in the most developed regions. This paper identifies the different drivers of heating and cooling energy demand, and decomposes this energy demand into key drivers based on a Kaya identity approach: number of households, persons per household, floor space per capita and specific energy consumption for residential heating and cooling; and GDP, floor space per GDP, and specific energy consumption for commercial buildings. This paper also reviews the trends in the development of these drivers for the present, future – and for which data were available, for the past – in 11 world regions as well as globally. Results show that in a business-as-usual scenario, total residential heating and cooling energy use is expected to more or less stagnate, or slightly decrease, in the developed parts of the world. In contrast, commercial heating and cooling energy use will grow in each world region. Finally, the results show that per capita total final residential building energy use has been stagnating in the vast majority of world regions for the past three decades, despite the very significant increases in energy service levels in each of these regions.

Contents

* Corresponding author. Tel.: +34 973 00 35 77.
E-mail addresses: vorsatzd@ceu.hu (D. Ürge-Vorsatz), lcabeza@diei.udl.cat (L.F. Cabeza).
[1] Tel: +36 1 327 3021.

http://dx.doi.org/10.1016/j.rser.2014.08.039
1364-0321/

1. Introduction and aims

Buildings and activities in buildings contribute to a major share of global environmental concerns [1]. Environmental pressures influenced by the quantity and quality of the energy in buildings are indoor and outdoor air pollution, related and additional health risks and damages, and energy dependence and insecurity. Buildings energy use is a major contributor to energy-related challenges to sustainable development such as deaths attributable to indoor cooking, insufficient energy resources to fuel economic development, lack of access to modern energy services for everyone, and climate change.

Much of these environmental problems are due to the energy that fuel buildings and activities within them [1–3]. More concretely, in 2010 the building sector used approximately 115 EJ globally, accounting for 32% of global final energy demand (24% for residential and 8% for commercial) [4] and 30% of energy-related CO_2 emissions [5]. The building sector is also responsible for approximately two-thirds of halocarbon and approximately 25–33% of black carbon emissions [3]. Moreover, the building sector used 23% of the global primary energy and 30% of the global electricity. Literature documents (such as Levine et al. [6] and the IEA [5]) that the energy consumption in buildings is growing and is expected to grow dynamically due to many reasons. However, there is limited consistent literature on understanding how this energy use is developing worldwide on a regional basis, and how different trends that influence energy use in buildings develop both on a historical basis as well as in the future. The authors of this paper have found a major literature gap in this area when working on assessing the literature for the Fifth Assessment Report of the IPCC. Understanding underlying trends in drivers and past energy use is crucial for future projections, modeling activities, policy design aimed at addressing environmental and social problems related to energy use in buildings, etc.

Therefore the purpose of this paper is to fill in this gap by a robust, detailed review and assessment of available data and literature related to building energy use and its drivers.

Attributing trends in energy use to drivers can be done using different methods; this paper uses the Kaya identity approach, consistently with the main underlying analytical framework used in the Fifth Assessment Report of the IPCC. However, when such approach is used, decomposition is very different for building energy end-uses mainly driven by physical characteristics such as building architecture and climate, i.e. heating and cooling, as opposed to energy end-uses whose consumption is driven mainly by the number of people in residential buildings or by activity in commercial and public buildings[2] such as appliance use (e.g., washing machines, telephones, etc.). As a result, decomposition analysis is also different for these two categories of building energy end-uses. Accordingly, this paper focuses on thermal energy uses, mainly heating and cooling with occasional coverage of hot water when it is difficult to disentangle these; while Cabeza et al. [7] covered trends in and drivers of energy end-uses related to appliances and other electricity-using equipment. The paper serves as a comprehensive, consistent and detailed resource for historic, present and future data on and trends in heating and cooling energy use and its drivers on a global as well as detailed regional basis that is also consistent with the related analysis and data presented by the Fifth Assessment Report of the IPCC. The interpretation of these data and trends is left for other papers as these can be different based on different approaches, purposes and methods; this paper serves as the basis for such work.

The paper will first present the main trends in the global building energy consumption as relevant to heating and cooling. Then the methodology for the decomposition analysis is reviewed. Trends in heating and cooling energy use and its drivers are analyzed in detail in the following sections. Finally the influence of the drivers on the regional level is presented. The primary purpose of this paper is to serve a source of the data, and not to understand in detail the trends of the different drivers, which would be the purpose of further research.

2. Background: key trends in global building energy use

According to the IEA [5], Fig. 1 shows that in the commercial sector, buildings decreased the use of coal from 21% in 1980 to 3% in 2010 and the use of oil from 28% to 15%; meanwhile, the use of natural gas remained constant at about 23–25% and the use of renewable at about 2–3%, and finally the use of electricity and heat increased from 26% in 1980 to 54% in 2010. On the other hand, in the residential sector (so-called "services" in the ETP 2012), the use of coal decreased from 10% in 1980 to 4% in 2010, the use of oil decreased from 15% to 10%, the use of natural gas increased from 17% to 20% and the use of renewables stayed constant at about 41–42%; in the residential sector the use of electricity and heat increased only from 16% in 1980 to 25% in 2010. It can be seen that in 2010, the world buildings energy consumption was quite distributed in different final energy carriers (renewables, electricity and heat, and natural gas dominating), while in the commercial sector more than half of the energy used is electricity and heat, and renewables are a very small part.

Fig. 2 shows the total energy consumption in residential buildings by final energy carrier and by region [5]. It can be seen that in all OECD countries, Americas and non-OECD-Europe and Eurasia, natural gas, followed by electricity, is the mostly used energy source, while in the rest of the regions biomass and waste is the predominant energy source.

Fig. 3 shows that space heating is 32–33% of the total energy use in buildings (in residential and commercial buildings, respectively) [4]. Domestic hot water represents 24% in residential buildings and 12% in commercial buildings. This paper only deals with part of the energy use in buildings: total final energy use from 1980 to 2010 and thermal energy for heating and cooling from 2010 to 2050, including hot water (from now on, called "heating and cooling building energy use (H&C BEU)").

3. Methodology

3.1. Drivers decomposition

Drivers contributing to significant increases in building energy use are population migration to cities, decreasing household size,

[2] Energy use in both types of end-uses is strongly determined by behavioral and cultural factors that are not covered in most of the decomposition and driver analysis beyond affluence or GDP.

increasing levels of wealth and lifestyle changes, including an increase in personal living space, the types and number of appliances and equipment and their use. 85% of growth in building energy use until 2050 will come from urban areas and 70% of the total from developing country cities [8]. Rapid economic development accompanied by urbanization and shifts from informal to formal housing is propelling significant building activity in developing countries [9].

Building-related emissions and mitigation strategies have been decomposed by identity logics, known as the Kaya decomposition, referring to one of the first authors to use it [10,11], or Kaya identity [12]. The factors commonly used are CO_2 intensity, energy intensity, structural changes, and economic activity, or the IPAT approach (Income–Population–Affluence–Technology approach) [13–16]. After its application to energy systems it has found widespread use in climate economics, e.g., [17]. Therefore, the authors of this paper will use this concept in identifying the drivers of the heating and cooling energy trends, such as activity drivers (*A*), use intensity drivers (TEI – technological energy intensity), and energy intensity drivers (SEI – structural/systemic energy intensity), not considering therefore the carbon intensity driver (CI):

$$CO_2 \text{ emissions} = CI * TEI * SEI * A \quad (1)$$

Drivers of energy consumption in buildings are many and from different nature. Carbon efficiency drivers are fuel switch to low-carbon fuels, building-integrated renewable energy sources, and other supply-side decarbonization; technological efficiency drivers are efficiency improvement of individual energy-using devices; systemic efficiency drivers are those which produce energy use reductions due to architectural, infrastructural and systematic measures; and demand reduction drivers are all measures that are beyond technological efficiency and decarbonization measures, such as impact on floor space, service levels, behavior, lifestyle, and use and penetration of different appliances. Here we will encapsulate all those drivers in the KAYA decomposition.

Heating and cooling energy use in residential buildings (H&C BEU) can be decomposed in several drivers following the Kaya

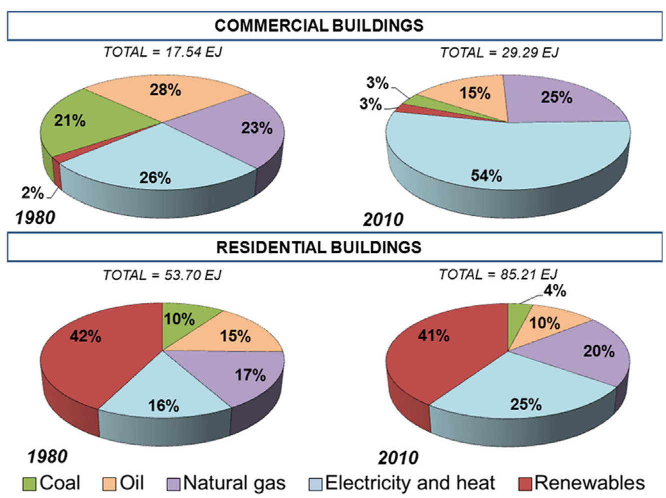

Fig. 1. World total final buildings energy consumption by final energy carrier [5].

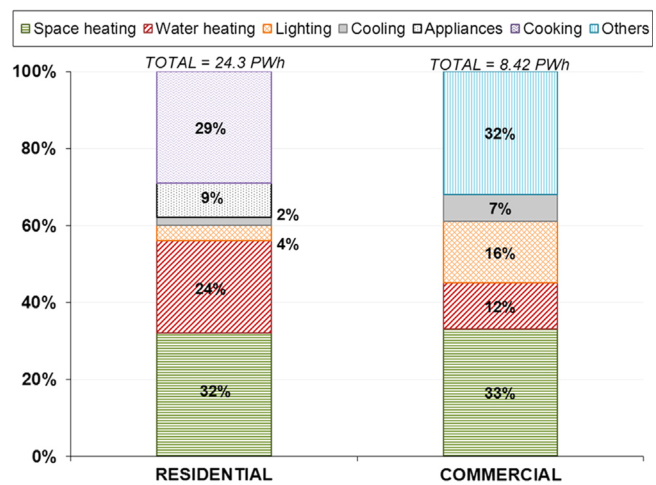

Fig. 3. Final building energy consumption in the world by end-use in 2010 (“Others” category includes IT equipment, etc.) [4].

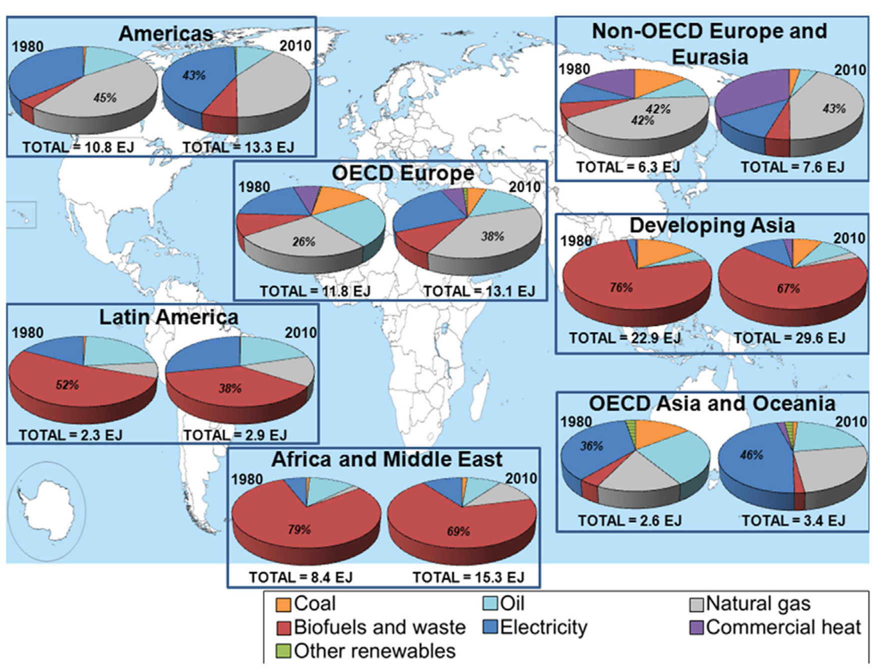

Fig. 2. Residential buildings total energy consumption by final energy carrier [5].

identity methodology, as shown in the following equation:

$$E_{resid}[\mathrm{kWh}] = h\frac{p}{h}\frac{A}{p}\frac{E}{A} \quad (2)$$

where E_{resid} is the energy use for heating and cooling in residential buildings, h is the number of households (activity driver), (p/h) is the number of persons living in each household, also called household size (activity driver), (A/p) is the floor area [m^2] per person (use intensity driver), and (E/A) is the energy [kWh] used for heating or cooling each unit of floor area [m^2], also called *specific energy consumption* (energy intensity driver). For commercial buildings, the heating and cooling use decomposed in drivers is presented as

$$E_{com} = GDP\frac{A}{GDP}\frac{E}{A} \quad (3)$$

where E_{com} is the energy use for heating and cooling in commercial buildings, GDP is the Gross Domestic Product [2005 US$] (activity driver), (A/GDP) is the floor area [m^2] per GDP (use intensity driver), and (E/A) is the energy [kWh] used for heating or cooling each unit of floor area [m^2], also called *specific energy consumption* (energy intensity driver).

3.2. Data sources

The *world population* (p) from 1980 to 2050 was obtained from United Nations, Department of Economic and Social Affairs [18]. The data was very complete and the only data missing is from countries with very little influence in the population of that region.[3]

The *number of households* (h) was obtained from the United Nations [19]. This document gives data for every 15 years in the period 1985–2050, and estimates the growth in each period. Data presented in this paper has been calculated for the period 1980–2050 in 10 years periods. Again the data was very complete and the only data missing is from a few countries, having only to highlight the missing data from Korea.[4]

The data on *floor area* (m^2) for the past was not available. The data on floor area dynamics and building heating and cooling energy use under Frozen Efficiency Scenario for future projections have been taken from the High Energy Building (3CSEP-HEB) model developed by the Centre for Climate Change and Sustainable Energy Policy (3CSEP) and commissioned by the Global Building Performance Network (GBPN [8]). The main aim of the 3CSEP-HEB model is to analyze heating and cooling energy use (understood as space heating and cooling as well as water heating) and related CO_2 emissions trends in buildings at the global and regional levels till 2050. For detailed information regarding the model's methodology, flow chart and assumptions, see [8]. This model is based on the performance-oriented approach to buildings energy analysis, considering buildings as holistic systems rather than the sum of the components. Therefore, for the space heating and cooling the overall energy performance of buildings is analyzed, regardless of the individual measures applied in each building. For water heating, however, the diversity of possible solutions is taken into account and for each individual technology, an average achievable efficiency is assumed.

There are three scenarios within the 3CSEP-HEB model with different levels of ambition for energy efficiency best-practices proliferation: deep efficiency, moderate efficiency and frozen efficiency scenario. In this paper, only the frozen efficiency scenario is used in order to demonstrate future building heating and cooling energy trends and floor area dynamics. The frozen efficiency scenario pictures a hypothetical future of global and regional building stocks in case no policy and technological developments will be taking place by 2050. It is reflected in the assumption that energy performance of new and retrofit buildings does not improve as compared to the 2005 levels. A similar assumption is used for water heating energy use: the fuel mix and efficiency of water heaters are “frozen” at the base year level. New advanced buildings are assumed only in Germany as 5% and in Austria as 10% of their new building stock and no advanced retrofit buildings are considered in any of the regions. New buildings consume 10–20% more than the national building codes or regional averages, while retrofit buildings consume only 10% less than standard buildings. Retrofit rate is fixed at 1.4% for all regions.

Estimation and projection of the floor area is the core part of the model. It is based on a comprehensive multi-level building classification, which distinguishes between buildings located in different regions, climate zones, urban and rural areas. The classification includes different building types: residential (single-family or multifamily) and commercial & public (C&P) buildings (offices, educational buildings, restaurants and hotels, retail and others) and different vintages: standard, new, advanced new, retrofit, advanced retrofit. Standard buildings are those ones, which had been built earlier than 2005, new and retrofit (and advanced new and retrofit) buildings refer to the ones constructed and renovated (respectively) during a particular year within the analyzed period.

All outlined building vintages and types are involved in the modeled annual building stock dynamics. Every year a certain share of the standard building stock (usually around 0.5%) is demolished and a certain portion is renovated (1.4–3%). Construction of new buildings is driven by factors, which differ for residential and commercial buildings. For the former it is population dynamics and region-specific floor area per capita. Estimation of the commercial floor area is determined by GDP (Market Exchange Rate) projections. C&P floor area of the region in 2005 is divided by GDP in 2005 and this constant is multiplied by GDP for each year to result in the C&P floor area demanded by each region.

The data on *Gross Domestic Product* (*GDP*) for the past was obtained from the IAE statistics [20]. Projections for GDP were borrowed from the scenarios of the MESSAGE model developed by International Institute for Applied Systems Analysis (IIASA) for the Global Energy Assessment [21–23]. All GDP data is in 2005 US$.

There was no data available on the thermal space heating and cooling and domestic hot water energy used in buildings for the past (E). The only data available was for total energy used in buildings, available from the IAE statistics [20]. This data is used as indicative in some parts of the paper. The data was very complete and the only data missing is from given years in a few countries with very little influence in the global values of the regions.[5]

In order to estimate projections of energy use for space heating and cooling for a certain year, region, climate zone, building type and building vintage respective floor area results are multiplied by the data on specific energy consumption. These data are coming from the database of exemplary buildings developed by 3CSEP

[3] Countries missing were Gibraltar in WEU; Antigua and Barbuda, Bermuda, Dominica, and St Kitts and Nevis in LAM; Seychelles in AFR; Chinese Taipei in CPA; and Kiribati in PAS.

[4] Countries missing were Korea in PAO, Gibraltar in WEU; Bosnia-Herzegovina, Serbia, and Montenegro in EEU; Antigua and Barbuda, Bermuda, Dominica, French Guyana, Grenanda, St. Kitts and Nevis, St. Lucia, and St. Vincent and Grenadine in LAM; Angola, Sao Tome and Principe, Seychelles, Sierra Leone, and South Africa (1980 and 1990) in AFR; Lebanon in MEA; Chinese Taipei in CPA; and Afghanistan and Kiribati in PAS.

[5] Countries missing were Gibraltar (2000) and Malta (1980) in WEU; Albania (1980–1990), Bosnia (1980), Croatia (1980), FYROM (1980), Serbia (1980), Montenegro (1980–2000), and Slovenia (1980) in EEU; All (1980), Azerbaijan (1980), and Kyrgyzstan (1980–2000) in FSU; Algeria(1990–2000), Bahrain (1980), Egypt (1990), Iraq (1980–2000), Lebanon (1980–1990), Libya (1980–2000), Qatar (1980), and Syria (1980) in MEA; and DPR Korea (1980–2000) in CPA.

through the analysis of a great variety of sources (see detailed information on the data sources in [8]). However, due to insufficient data availability for all required data-points and limited data precision, certain assumptions had been made to fill in the gaps for certain regions.

Different building vintages have different levels of specific energy consumption for space heating and cooling. General rules-of-thumbs applicable to all regions are (1) standard buildings are the most energy-consuming; (2) specific energy consumption of retrofit buildings constitutes a certain share of the one of standard ones (usually 70–90% depending on the scenario); (3) energy performance of new buildings is in compliance with the average level of the Building Codes or corresponds to the regional level (or 10–20% higher depending on the scenario); (4) energy performance of advanced buildings is coming from reported regional best-practices and is approximately at the passive house level (15–30 kWh/m^2/year depending on the building type and climate zone); (5) specific energy consumption for space heating and cooling of advanced retrofit buildings is usually slightly higher than the one of advanced new buildings; and (6) if an advanced

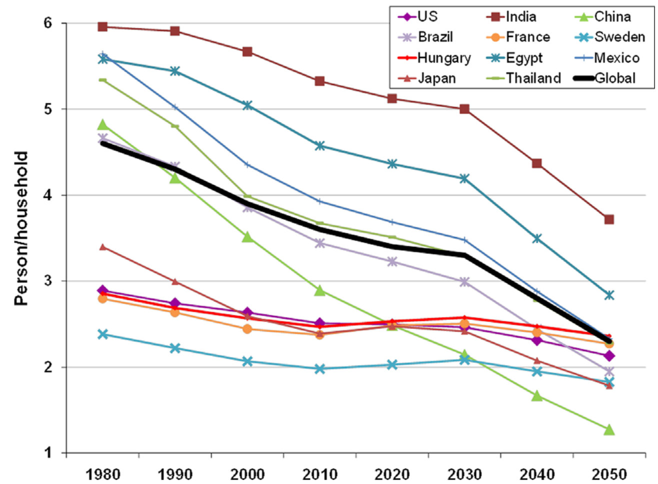

Fig. 5. Person per household in some selected countries. Data from United Nations [18,19].

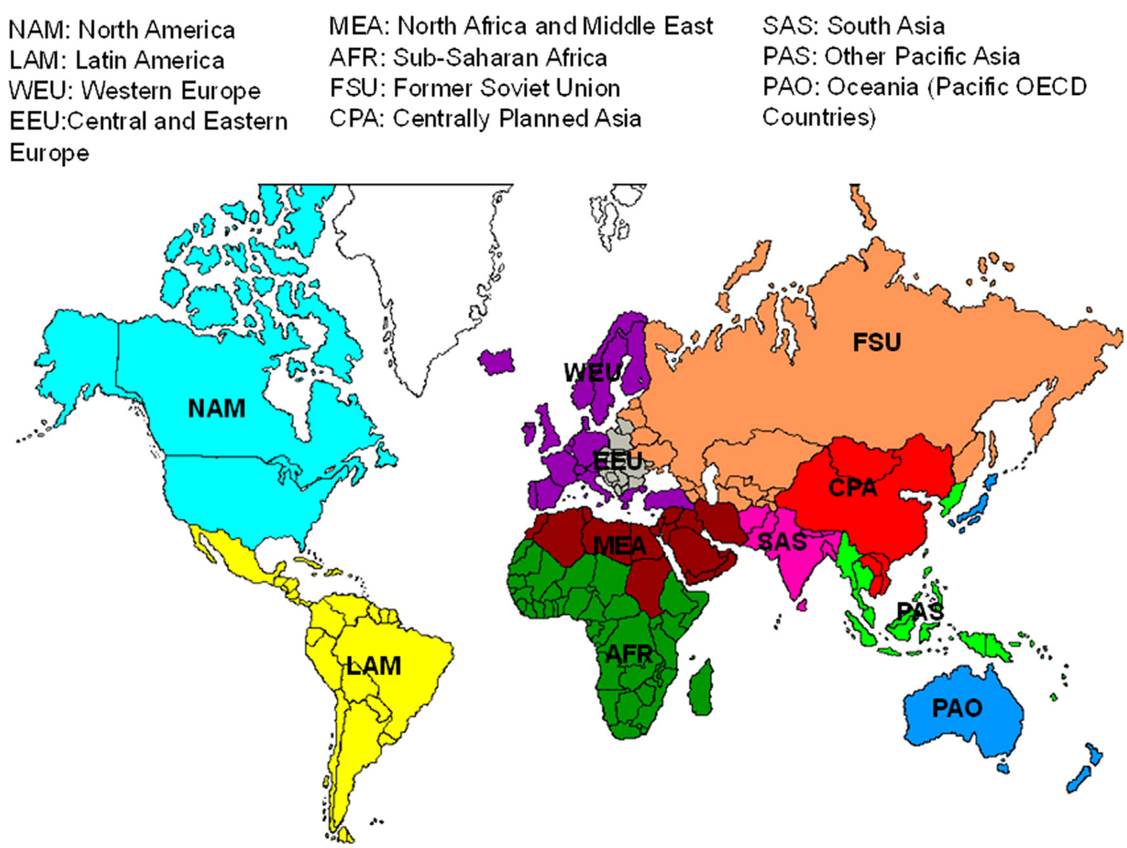

Fig. 4. Regions considered [24].

Table 1
Global residential heating and cooling energy consumption projections (based on a frozen efficiency scenario) and its drivers 2010–2050. Data from Ref. [1].

Year	Energy (PWh)	Kaya drivers				Other drivers	
		Households (h, billions)	Persons per household (p/h)	Per capita floor area (m^2/p)	Specific energy consumption (kWh/m^2/year)	Population (billions)	Floor area (m^2)
2010	16	1.9	3.6	20.7	110	6.8	1.41×10^{11}
2020	19	2.2	3.4	22.7	110	7.7	1.76×10^{11}
2030	22	2.6	3.3	25.0	110	8.4	2.11×10^{11}
2040	26	3.2	2.8	26.8	100	9.1	2.43×10^{11}
2050	28	4.1	2.3	28.5	100	9.6	2.74×10^{11}

performance level is reached in a certain building, it can be replicated in other buildings belonging to the same building type and climate zone.

3.3. Regional distribution

All results are presented either globally for the world or for the different regions as grouped by IPCC [24,25]. The regions considered are presented in Fig. 4.

4. Results

4.1. Overview of the global trends in the key drivers

Table 1 shows the global residential heating and cooling energy consumption projections and its drivers from 2010 to 2050. It can be seen that the global specific energy consumption is not

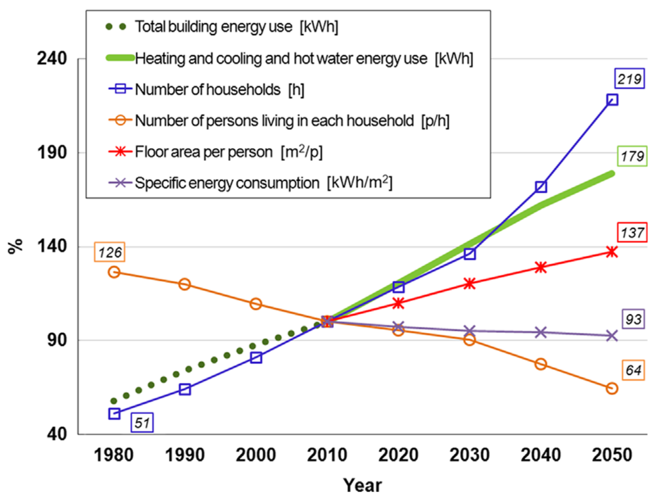

Fig. 6. Trends in the different drivers of energy consumption in residential buildings in the world 1980–2050. Data for *h* and *p* are from United Nations [18,19], total building energy use (1980–2010) is from IEA [3], projections on floor area and heating and cooling energy use (2010–2050) are based on a frozen efficiency scenario [1].

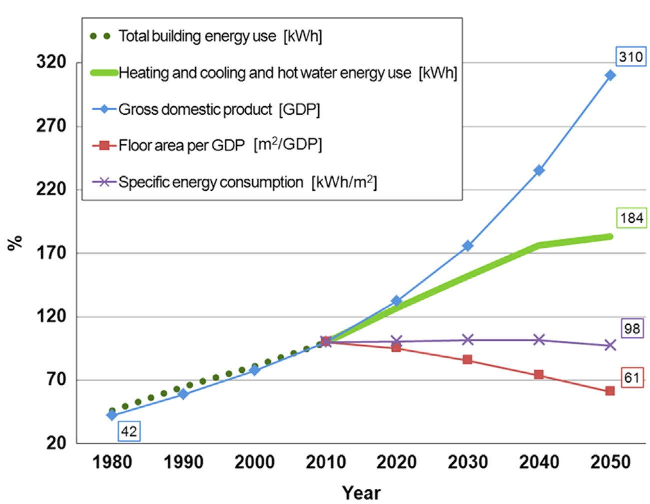

Fig. 7. Trends in the different drivers of energy consumption in commercial buildings in the world 1980–2050. Data for *h* and *p* are from United Nations [18,19], total building energy use (1980–2010) is from IEA [3], projections on floor area and heating and cooling energy use (2010–2050) are based on a frozen efficiency scenario [1].

projected to increase. The global floor area per capita is projected to increase only around 38% in the next four decades Because each household has to be serviced (one kitchen, one or two bathrooms, etc.) the energy demand increases due to that. Per capita floor area is expected to increase by almost 50%, so people will live in much more space than today in 40 decades; in total this is going to drive the global floor space at 41%. Moreover, the diversity between regions and countries is very high in this driver due to historical trends. This is shown in Fig. 5, where it can be seen that India has higher number of persons per household, but with a trend very similar to the global one. Such a trend is also followed by another developing country such as Egypt. Mexico and Brazil show a higher decreasing slope, but China has the highest decreasing slope, probably due to its policies of only one child allowed per couple. It is interesting to see that the developed countries show a lower number of persons per household, with a higher decreasing slope in Japan than in the others countries shown, US, Hungary and Sweden (with the lowest number of person per household in the world).

Table 1 also shows that while population is increasing by 41% from 2010 to 2050, the number of households will almost double (115%) and floor space increases by 94%. This reinforces that the number of households is a better indicative driver to use for residential energy consumption projections than population.

In Fig. 5 it can also be seen that in general per capita household size is largely converging (as seen in the selected countries) between 2 and 3, except for China where it is expected to be 1.3 by 2050. The shrinking household size has an important effect in the BEU by fewer opportunities of sharing energy services such as heated, cooled, lighted living space, laundering, refrigerators, etc.

Fig. 6 shows that between 2010 and 2050, in a frozen scenario, the global heating and cooling energy consumption increases by 80%. It can be seen that in the whole period evaluated (1980–2050) the strongest driver is the increase of number of households, which is growing stronger even in the next three decades. Projections show that the size of households is decreasing due to urbanization, divorce rates [27], mobility of young people, etc., driving energy use up. It should be highlighted that because the past global heating and cooling energy consumption was not available, in Fig. 6 and following figures the total energy buildings use is included as a rough estimate.

Table 2 shows that although population is increasing the commercial building energy used is more related to economy activity, and economy activity will increase much more than population; therefore more dynamic increase is expected in the commercial sector than in the residential one. Figs. 6 and 7 show the trends in the drivers of energy consumption in residential and commercial buildings by key world region, respectively. In Fig. 7 it can be seen that while the residential building energy use increased only by 65% (Fig. 6), the commercial one almost doubled. The frozen

Table 2
Global commercial heating and cooling energy consumption projections (based on a frozen efficiency scenario) and its drivers 2010–2050. Data from Ref. [1].

Year	Energy (PWh)	Kaya drivers			Other drivers
		GDP (2005 US$)	Floor area/GDP (m^2/2005 US$)	Specific energy consumption (kWh/m^2/year)	Floor area (m^2)
2010	6.0	5.0×10^{13}	9.9×10^{-4}	120	4.98×10^{10}
2020	7.6	6.6×10^{13}	9.4×10^{-4}	120	6.27×10^{10}
2030	9.1	8.8×10^{13}	8.4×10^{-4}	120	7.45×10^{10}
2040	10	12×10^{13}	7.3×10^{-4}	120	8.65×10^{10}
2050	11	16×10^{13}	6.0×10^{-4}	120	9.37×10^{10}

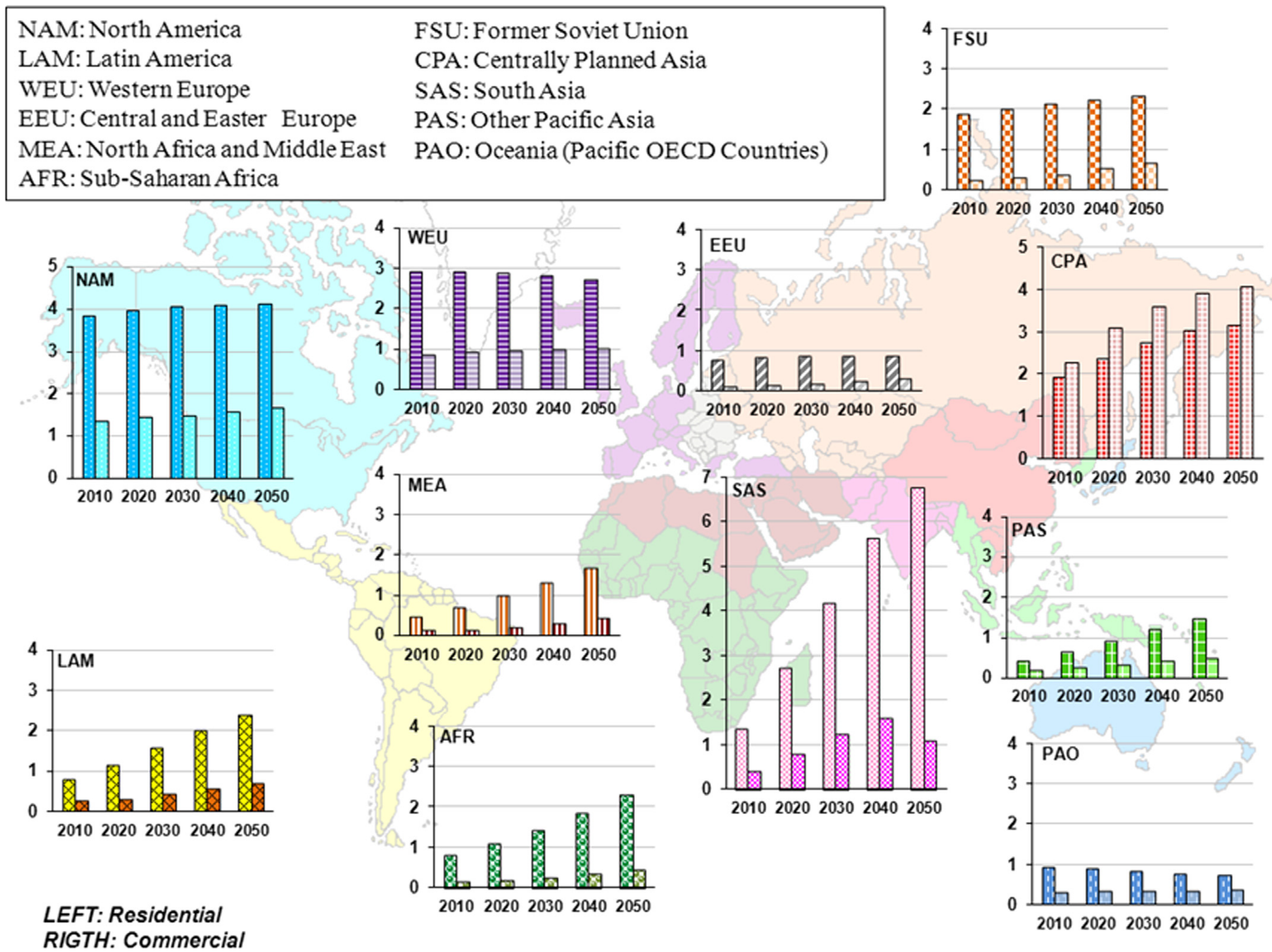

Fig. 8. Heating and cooling energy consumption in the building sector in the different regions of the world in residential and commercial buildings, 2010–2050. Projections (2010–2050) are based on a frozen efficiency scenario [1].

scenario used in this paper shows that in the future, residential energy use projects an increase of 80% between 2010 and 2050, while for the commercial energy use will increase about 75%. While GDP increases by 220% energy use is expected to increase only 83% due to the elasticity of floor area by GDP decreasing.

Both in residential and commercial building sectors a slight decrease in specific energy consumption is expected, since this value is the composite of two big trends in both type of buildings, one is the continuous efficiency gains and the other is the continued service levels in space conditioning (today not all areas are heated or air conditioned to full thermal comfort levels, especially in some regions of the world, as will be shown below).

4.2. Regional analysis of the trends in the drivers

4.2.1. Trends in heating and cooling energy consumption

For residential buildings, Fig. 8 shows that basically by mid-century five regions will dominate the world buildings heating and cooling energy use: NAM, WEU, CPA, with SAS dominating it. Residential energy use is increasing strongly only in six regions, while it is stagnating or decreasing in the other six regions considered. For example, in CPA it is heavily increasing until 2040 and then it starts stagnating.

Comparing residential and commercial buildings, residential energy use dominates being at least a factor of two or more higher all over the world except in CPA, where the commercial buildings energy use already today exceeds the residential one.

Finally, Fig. 8 also shows that commercial buildings energy use keeps increasing during the studied period basically everywhere except for PAO and a small decrease in SAS at the end of this period.

Fig. 9 shows that the global trends mark very different trends in the different regions. For example in SAS the building heating and cooling energy use (H&C BEU) could increase by fivefold by the end of the period, while in WEU it will decrease even in the frozen efficient scenario. The most dynamic increases are expected in LAM, MEA, AFR, SAS and PAS. Each of these regions at least will triple their residential H&C BEU until the middle of the century.

As for the drivers, the changes in household size (p/h) are more moderate. Many regions it has decreased approx. 10–20% since 1980–2010 (NAM, WEU, EEU, MEA and SAS) and only for a few ones was this figure above 30–65% (LAM, FSU, CPA, PAO, PAS and AFR). For the future, household size is expected to continue its most dynamic decrease to almost halve in CPA, MEA, AFR, SAS, PAS and LAM. In developed regions this driver will decrease only moderately (from 10% to 25%).

The per capita floor area of buildings is not available for past trends. It is expected to significantly grow until 2050 in several regions with over-doubling in LAM, MEA, SAS, and PAS. In some developed regions it is actually projected to decrease such as in NAM and WEU around 11–12%, likely because of the limited availability of land, due to urbanization (in developed regions

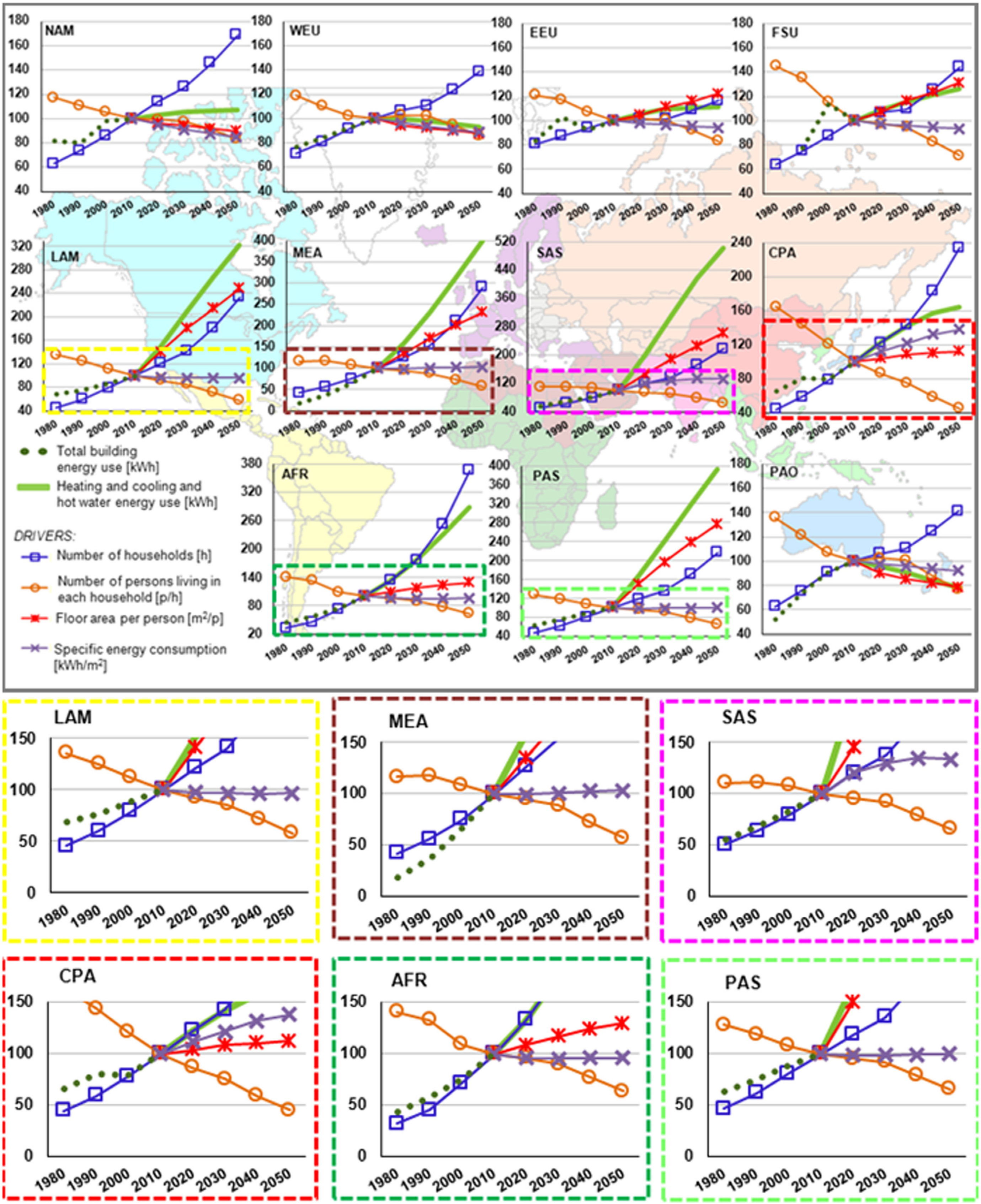

Fig. 9. Trends in the drivers of energy consumption in residential buildings by key world region. Data for *h* and *p* are from United Nations [18,19], total building energy use (1980–2010) is from IEA [3], projections on floor area and heating and cooling energy use (2010–2050) are based on a frozen efficiency scenario [1].

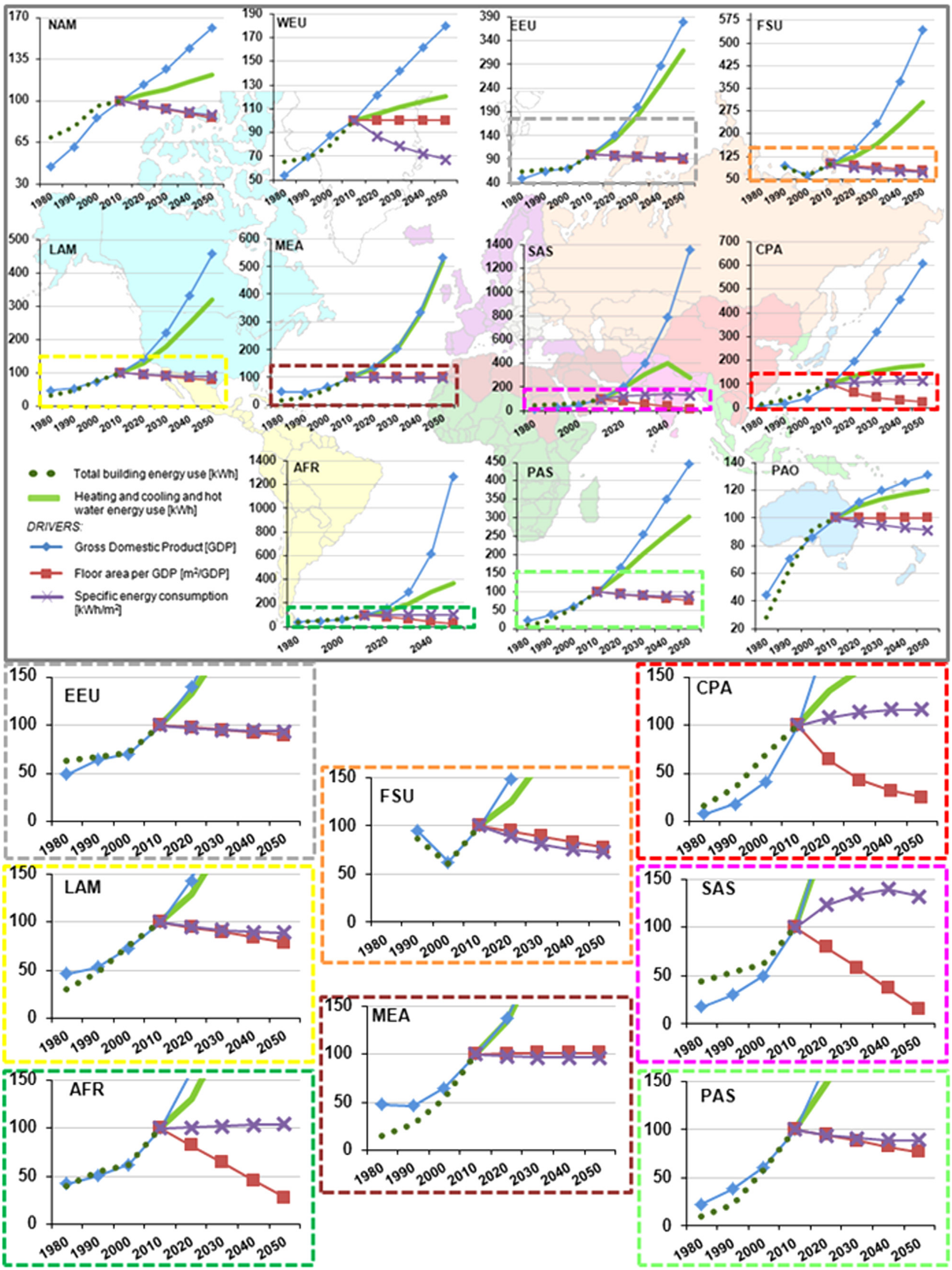

Fig. 10. Trends in the drivers of consumption in commercial buildings by key world regions 1980–2050. Note that in order to show the trends in different world regions better, the scale varies by region. Data for *h* and *p* are from United Nations [18,19], total building energy use (1980–2010) is from IEA [3], projections on floor area and heating and cooling energy use (2010–2050) are based on a frozen efficiency scenario [1].

urban dwellings are smaller), and divorce [27]. Interestingly in some developing regions household size is also not expected to increase that significantly, such as CPA and AFR, which maybe the composite result of increasing trends by increasing affluents and increasing urbanization that tends to limit floor space.

Specific energy consumption also cannot comment on the past due to the lack of floor space and H&C data. In terms of the future, this driver is not going to change significantly during the period due to the two opposite trends driving this indicator, efficiency increase and service levels increase. It will exhibit the largest, but still moderate, in CPA and SAS, with about roughly 38% and 33% increase respectively. It is projected to be stagnated or very moderate decrease or increase in EEU (−6%), FSU (−7%), WEU (−12%), NAM (−16%), LAM (−4%), MEA (3%), PAS (0%), AFR (−4%), and PAO (−8%). In regions relying in biomass heating, with a shift of fuel significant efficiency gains may be obtained, but again they may be compensated by more space heated to higher temperatures.

In Fig. 10 it can be seen how for commercial buildings the building H&C energy use is expected to increase in every region, although at different rates. A big increase, almost tripled, will be seen in FSU, EEU, PAS, SAS, LAM and AFR. The strongest increase will be in MEA, increasing by fivefold. The most moderate increases are expected in NAM (21%), WEU (21%) and PAO (20%).

The key driver of commercial H&C BEU, GDP, is expected to grow in every region, again with very different trends. For instance, while PAO will only increase by 30%, and NAM and WEU by roughly 60–80%, other regions will multiply their GDP such as FSU, LAM, PAS, CPA and MEA (five- to six-fold), EEU (over fourfold), and SAS and AFR (more than ten times). How this very dynamic increase exactly influences H&C CBEU will largely be determined by the elasticity changes of commercial floor space to GDP trends.

Similarly to the residential sector, trends in specific energy consumption are going to be significantly less dramatic than the other drivers. SEC is likely to remain mostly constant or moderate change, most notably it is expected to decrease by over 33% in WEU, due to strong building energy efficiency regulations (in the frozen efficiency scenario). The one region which will have a notable increase is SAS (32%), which trend is likely to be driven by the substantially increased use of air conditioning of commercial spaces.

Fig. 11 shows the residential and commercial total building energy use per capita. It demonstrates a very important trend in BEU; it attests in the last three decades residential BEU has roughly stagnated in the vast majority of the world (NAM, WEU, EEU, LAM, AFR, SAS, CPA and PAS). It increased notably only in FSU (30%), PAO (25%) and MEA (80%). In all other regions it has either slightly decreased or increased by less than 10%. This trend is robust against the level of development and climate type, because each type of region shows this trend, even in the very dynamically developing, such as CPA and SAS. This is an unexpected trend if we consider the big increase in affluence. In contrast, commercial BEU increased in all regions. Most notably it increased in MEA, PAS and

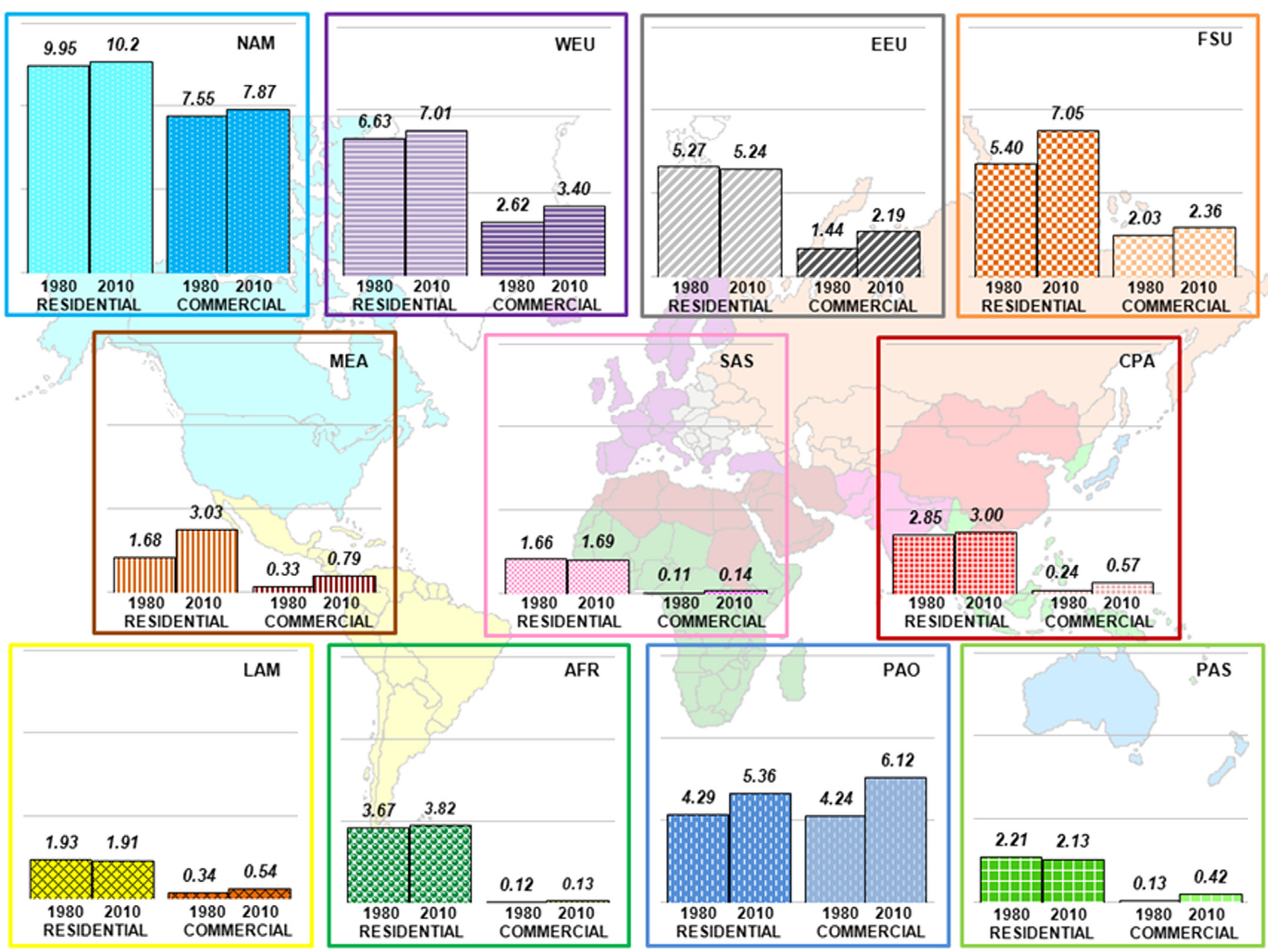

Fig. 11. Residential and commercial per capita total energy use by key world region [MWh/per capita/year] in 1980 and 2010. Data E from IEA statistics [3] and p from United Nations [12].

CPA; by over two- to three-fold. In regions like WEU, SAS, PAO, LAM and EEU the increase is between 20% and 60%. The increase was less than 10% in NAM, AFR and FSU.

With regard to the importance of heating and cooling in total building energy use, the picture is very diverse with 18–73%, and the trends are not trivial (Fig. 12). The highest shares of thermal building conditioning in these sectors energy use are in the commercial buildings of developing countries in hot (and partially humid) climates: 73% in CPA and 64% in SAS. This is likely to be the result of a thermally poorly built commercial building sector (such as appealing large glazed surfaces that result in major heat gains), supplied with inefficient cooling technologies, combined with the fact that the penetration of other electricity-using commercial equipments is not so high yet as in the most developed countries. Other regions with high thermal conditioning energy use shares are the residential buildings in NAM (52%), FSU (48%) and EEU (55%), and WEU (46%). In the FSU and EEU this is due to the legacy of poor thermal efficiency of the building stock due to the high energy price subsidies in the soviet era [26], in combination with cold climates. In North America and WEU, it is also likely to point at the fairly low level of thermal efficiency of the building stock and heating/cooling equipment.

Heating and cooling plays the smallest role in commercial buildings in MEA (18%) and PAO (20%), and residential buildings in AFR (20%). While the latter is expected due to the climate and diverse ways of adaptation to living in a hot climate, the first two are more surprising because these shares are lower than in the residential sector (over double in share – 49% – in PAO and slightly higher in MEA with 24%), and commercial buildings are often cooled more than residential ones due to higher needs of more comfortable temperatures to ensure productivity and due to higher internal heat gains due to more electricity-using equipment and lighting during the day.

4.2.2. Trends in specific space heating and cooling and domestic hot water energy consumption

Since sometimes it is difficult to separate space heating and cooling (SH&C) energy use and domestic hot water (DHW) energy use, Fig. 13 includes both H&C and DHW in residential and commercial buildings separately (data from Fig. 13 is detailed in Table 3, in the Annex of this paper). DHW in residential buildings represents a small end use of heating and cooling, with the largest shares in EEU homes and LAM (closer to 35–40%), in the other regions it is only between 20% and 30%. In most regions commercial water heating energy use represents a smaller share both in absolute and relative terms than residential, except in FSU, Africa and the Pacific.

The relation of energy intensity in the commercial vs. residential sector is different in the different regions. The largest difference is in CPA, where energy intensity in commercial buildings is almost double the residential sector in 2010, and in MEA, SAS, PAS and AFR is 10–30%. The relationship between residential and commercial energy intensity does not change throughout the projection period, except in FSU, where the presently higher commercial energy intensity will gain more in efficiency terms than the residential sector, and will consume less in 2050 per square meter.

By far the highest SH&C figures are in FSU, largely due to the legacy of communist energy subsidies as well as to a harsh climate. In the other developed regions, with mostly moderate continental climate, both residential and commercial sets are a bit under

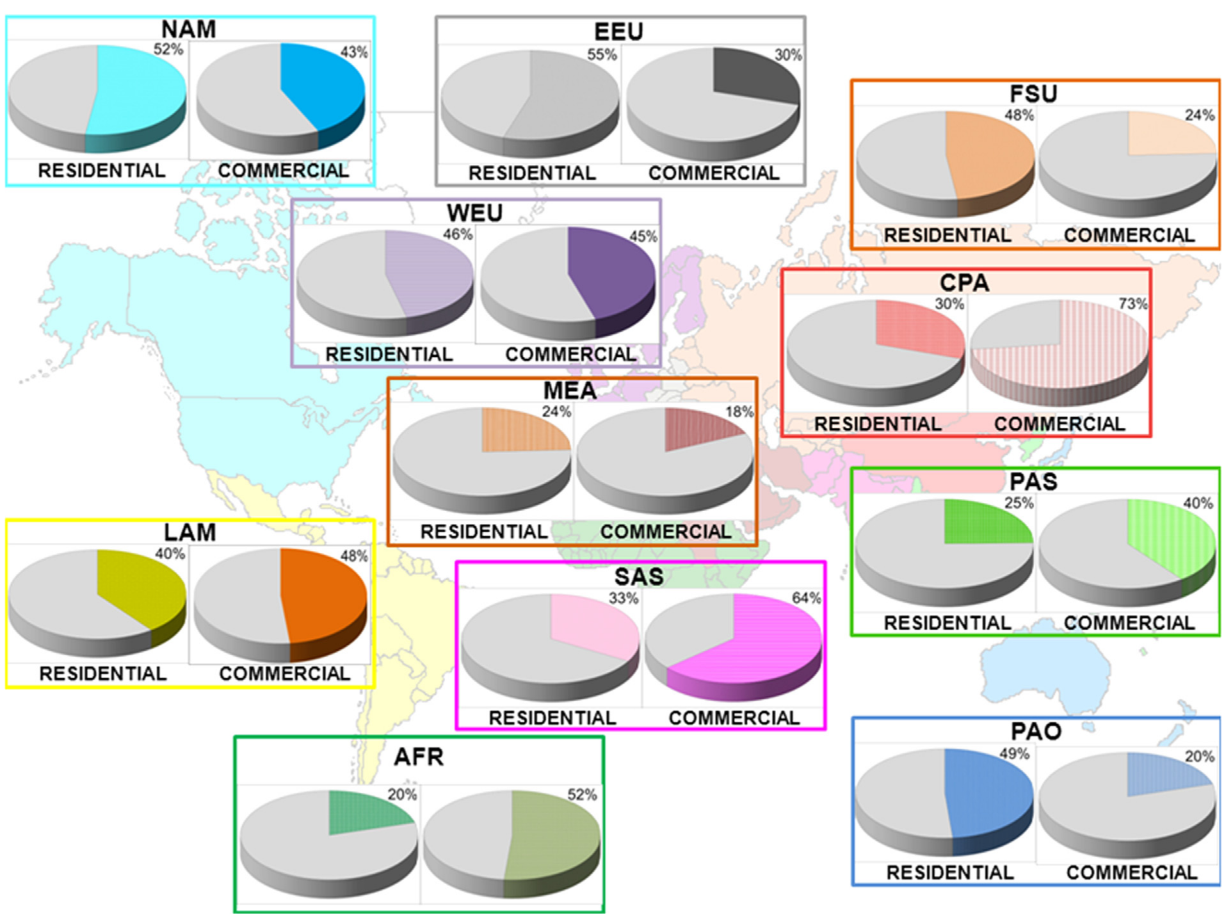

Fig. 12. Heating and cooling energy consumption in 2010 of residential and commercial buildings in the different world regions. Total building energy use is from IEA [3], projections on heating and cooling energy use are based on a frozen efficiency scenario [1].

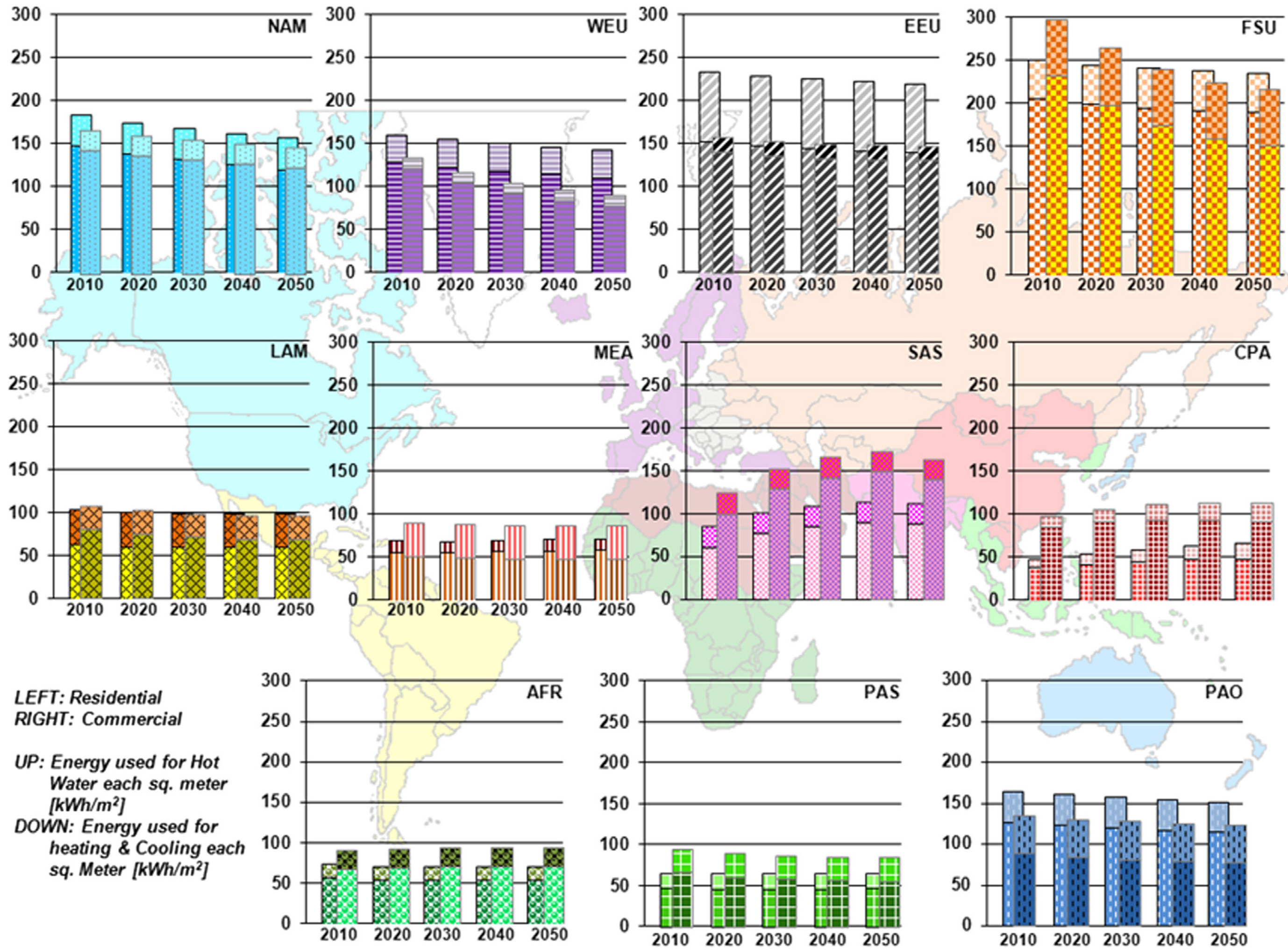

Fig. 13. Specific energy used for heating, cooling and hot water in residential and commercial buildings by key world region in kWh/m^2 (2010–2050). Data based on a frozen efficiency scenario [1].

150 kWh/m^2/year. And, the frozen efficiency scenario will only decrease substantially in WEU, due to strong building efficiency policies. Heating and cooling energy intensity is projected to increase only in SAS and CPA slightly, with a bit stronger increase in the next two decades in SAS.

In the less developed regions of the world and CPA, residential SH&C is around 50 kWh/m^2/year, and it is not expected to grow significantly even until the end of the projection period despite the projected increases in affluence, floor space, and service levels.

5. Limitations and research needs

It is important to acknowledge that there is a significant uncertainty in all these figures with the accuracy of input data and thus projections significantly varying across regions and variables. Data on population GDP, households are more reliable, whereas, floor space, building energy use, specific energy consumption are much more uncertain, especially in most developing countries, where such data are neither collected nor reported.

As a result there is a significant need for a more consistent and comprehensive data collection and reporting related to building energy use worldwide, with some minor exceptions.

Whereas projections have been made for the building related energy use, heating and cooling related data from the past is not available except for some regions. A highlight on data missing is the present and past floor space for many regions.

6. Conclusions

The purpose of this paper was to provide an authoritative, consistent and comprehensive source of information on thermal energy use in buildings, its drivers, and their past, present and future trends on a global and regional basis, in a consistent manner with data and trends efforts of researchers contributing to the work of the Intergovernmental Panel on Climate Change (IPCC). Such information serves as the basis for relevant modeling work, policy preparatory work and other research. Therefore the paper did not intend to interpret these trends beyond some clear, simple interactions, but invites researchers to analyze and assess this information.

Energy use in buildings forms a large part of global and regional energy demand – with 32% of global final energy demand, 30% of energy-related CO_2 emissions, app. one-third of black carbon emissions. Thermal energy uses account for an important, but variable part of this demand. Globally, over 60% of residential and almost 50% of commercial building energy are demanded for thermal uses; with higher contribution from water heating in residential buildings, and from cooling in commercial. Within this, space heating comprises 32–33% of global total building energy

use. The importance of heating and cooling in total building energy use is very diverse with this share varying between 18% and 73%. The highest are in the commercial buildings of developing countries in hot (and partially humid) climates: 73% in CPA and 64% in SAS; and the smallest in commercial buildings in MEA (18%) and PAO (20%), and residential buildings in AFR (20%).

Biomass is still far the dominant fuel when a global picture is considered, covering most of the energy needs of the poor in the least developed countries, used with very low efficiencies. The role of electricity is substantially growing, presently accounting for over half of commercial building energy use. In developed countries, it fuels 12–43% of building energy needs. The direct use of coal is disappearing from this sector, largely replaced by electricity and natural gas in the most developed regions.

The paper has identified the different drivers of heating and cooling energy demand; and decomposed this energy demand into key drivers based on a Kaya identity approach: number of households, persons per household, floor space per capita and specific energy consumption for residential heating and cooling; and GDP, floor space per GDP, and specific energy consumption for commercial buildings. The rest of the paper then focused on reviewing the trends in the development of these drivers for the present, future – and for which data were available, for the past (the lack of comprehensive global data on either floor space or heating energy consumption) in 11 world regions as well as globally.

The development of these key drivers influences building energy use in different directions, although presently the composite in a business-as-usual scenario almost exclusively is a projected growth. Although autonomous and policy-induced efficiency gains are bringing specific energy consumption down in every region where heating and cooling energy service levels are saturated (in areas where indoor temperatures of used spaces are far from comfortable levels, these values will continue to increase despite efficiency improvements), the very dynamic increases in the number of households – either driven by population increase, immigration, or by fragmenting households – combined with in most regions still increasing per capita living space, significantly outpace this improvement. Trends in drivers are similar for the commercial sector: dynamically increasing commercial activity, indicated by GPD, is the strongest factor in driving heating/cooling energy use in this building type up, but this growth is moderated by a slowly decreasing elasticity, i.e. less new floor area per GDP, as well as gradual efficiency gains. Nevertheless, commercial heating and cooling energy use is still expected to strongly grow until the middle of the century, with an app. 84% projected increase by 2050 as compared to 2010. This figure is 79% for residential heating and cooling.

In a business-as-usual scenario, total residential heating and cooling energy use is expected to more or less stagnate, or slightly decrease, in the developed parts of the world (NAM, WEU, FSU, ad PAO). In contrast, commercial heating and cooling energy use will grow in each world region. Most dynamic growth in the next four decades is expected in SAS (including India) where the baseline scenario indicates an increase by almost six-fold. Even considering the uncertainty of this number, the very large expected increase is much higher than any other world region – with (AFR, MEA, PAS, LAM and PAS) less than tripling. Specific energy consumption is expected to decrease in all world regions, even if very slowly, except for CPA and SAS where 10–25% increase is expected throughout the period due to increasing service levels.

A somewhat surprising, but robust trend is that per capita total final residential building energy use has been stagnating in the vast majority of world regions for the past three decades, despite the very significant increases in energy service levels in each of these regions, indicated by many new appliances supplying more comfort in homes, including a major boost in entertainment, information, communication and media services. Perhaps this trend is the most important in this paper: if efficiency gains can continue to compensate for improvements in energy service levels on an individual basis, this could provide opportunities to turn global building energy use down in the longer term – but this is the scope of another paper.

Table 3
Data of specific energy used for heating, cooling and hot water in residential and commercial buildings by key world region in kWh/m^2 (2010–2050). Data based on a frozen efficiency scenario from Ref. [1].

	SH&C [kW/m^2]					HW [kW/m^2]				
	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050
RESIDENTIAL										
PAO	126.1	122.4	119.1	116.0	113.4	36.6	36.6	36.6	36.6	36.6
NAM	147.5	138.4	131.0	124.9	119.7	36.4	36.4	36.4	36.4	36.4
WEU	128.3	123.1	118.4	114.2	110.4	32.0	32.0	32.0	32.0	32.0
EEU	152.6	148.1	144.8	141.8	139.1	80.2	80.2	80.2	80.2	80.2
FSU	205.1	198.4	194.5	191.6	189.0	46.4	46.4	46.4	46.4	46.4
LAM	63.3	60.2	59.5	59.3	59.6	40.0	40.0	40.0	40.0	40.0
AFR	56.2	53.4	52.9	53.0	53.4	17.5	17.5	17.5	17.5	17.5
MEA	55.6	55.1	56.0	57.4	58.0	12.9	12.9	12.9	12.9	12.9
CPA	37.4	41.2	43.8	46.8	47.5	9.9	11.9	13.7	15.8	17.8
SAS	60.1	77.1	85.0	89.2	88.2	24.0	24.0	23.9	24.0	24.0
PAS	46.4	45.5	45.6	45.9	46.5	18.6	18.6	18.6	18.6	18.6
COMMERCIAL										
PAO	87.3	83.2	80.3	77.9	75.8	46.3	46.3	46.3	46.3	46.3
NAM	144.7	138.4	133.3	128.5	124.6	23.6	23.6	23.6	23.6	23.6
WEU	120.1	103.1	91.5	83.0	76.5	12.6	12.6	12.6	12.6	12.6
EEU	141.4	137.0	134.1	132.4	131.4	16.2	16.2	16.2	16.2	16.2
FSU	231.2	198.1	173.9	158.4	150.4	66.2	66.2	66.2	66.2	66.2
LAM	79.4	74.0	70.2	68.0	67.6	27.8	27.8	27.8	27.8	27.8
AFR	61.2	61.9	63.0	63.9	64.3	20.6	20.6	20.6	20.6	20.6
MEA	50.0	48.3	47.0	46.8	46.8	39.9	39.9	39.6	39.9	39.9
CPA	84.9	90.3	93.1	93.4	90.5	12.7	15.3	17.8	20.4	22.9
SAS	99.6	128.1	141.6	148.4	139.3	24.0	24.0	23.9	24.0	24.0
PAS	66.4	60.5	57.7	56.1	55.9	28.4	28.4	28.4	28.4	28.4

Acknowledgments

The work is partially funded by the Spanish Government (ENE2011–28269-C03-02 and ENE2011-13511-E). The authors would like to thank the Catalan Government for the quality accreditation given to their research group GREA (2014 SGR 123) and research group DIOPMA (2014 SGR 1543).

Annex

See Table 3.

References

[1] Ürge-Vorsatz D, Petrichenko K, Staniec M, Eom J. Energy use in buildings in a long-term perspective. Curr Opin Environ Sustain 2013;5(2):141–51.

[2] Grubler A, TB Johansson L Mundaca N Nakicenovic S Pachauri K Riahi, et al. Chapter 1 – energy primer. In: Global energy assessment – toward a sustainable future. Cambridge, UK and New York, NY, USA: Cambridge University Press; Laxenburg, Austria: International Institute for Applied Systems Analysis; 2012. p. 99–150.

[3] Ürge-Vorsatz D, Eyre N, Graham P, Harvey D, Hertwich E, Jiang Y, et al. Chapter 10 – energy end-use: building. In: Global energy assessment – toward a sustainable future. Cambridge, UK and New York, NY, USA: Cambridge University Press; Laxenburg, Austria: International Institute for Applied Systems Analysis; 2012. p. 649–760.

[4] IEA Online Data Services. Available at: 〈http://data.iea.org/ieastore/statslisting.asp〉.

[5] International Energy Agency. Energy technology perspectives 2012. Paris: OECD/IEA; 2012.

[6] Levine M, Ürge-Vorsatz D, Blok K, Geng L, Harvey D, Lang S, et al. Residential and commercial buildings. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, editors. Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007. p. 387–446.

[7] Cabeza LF, Ürge-Vorsatz D, McNeil MA, Barreneche C, Serrano S. Investigating greenhouse challenge from growing trends of electricity consumption through home appliances in buildings. Renew Sustain 2014;36:188–93.

[8] Ürge-Vorsatz D, Petrichenko K, Antal M, Staniec M, Labelle M, Ozden E, et al.. Best Practice Policies for Low Energy and Carbon Buildings. A Scenario Analysis. Budapest, Hungary: Research report prepared by the Center for Climate Change and Sustainable Policy (3CSEP) for the Global Best Practice Network for Buildings. 〈http://www.globalbuildings.org/global-projects/〉; 2012.

[9] WBCSD (2007). Energy efficiency in buildings facts and trends. World Business Council for Sustainable Development, Geneva, Switzerland.

[10] Ehrlich PR, Holdren JP. Impact Popul Growth Sci 1971;171:1212–7.

[11] Kaya Y. Impact of carbon dioxide emission control on GNP growth: Interpretation of proposed scenarios (IPCC Response Strategies) Working Group Memorandum; 1989.

[12] Hoffert HI, Caldeira K, Jain AK, Haites EF, Harvey LDD, Potter SD, et al. Energy implications of future stabilization of atmospheric CO_2 content. Nature 1998;395:881–4.

[13] MacKellar FL, Lutz W, Prinz C, Goujon A. Population, households and CO_2 emissions. Laxenburg, Austria: International Institute for Applied Systems Analysis; 1995.

[14] Isaac M, Van Vuuren DP. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 2009;37:507–21.

[15] Zhang M, Mu H, Ning Y, Song Y. Decomposition of energy-related CO_2 emission over 1991–2006 in China. Ecol. Econ. 2009;68:2122–8. http://dx.doi.org/10.1016/j.ecolecon.2009.02.005.

[16] O'Mahony T, Zhou P, Sweeney J. The driving forces of change in energy-related CO_2 emissions in Ireland: A multi-sectoral decomposition from 1990 to 2007. Energy Policy 2012;44:256–67. http://dx.doi.org/10.1016/j.enpol.2012.01.049.

[17] Nakicenovic N. Socioeconomic driving forces of emissions scenarios. In: Field CB, Raupach MR, editors. The global carbon cycle: integrating humansclimate, and the natural world. Washington, DC: Island Press; 2004. p. 225–39.

[18] United Nations, Department of Economic and Social Affairs, Population Division. World population prospects: the 2010 revision [CD-ROM Ed.]; 2011.

[19] United Nations. Centre for human settlements. Cities in a globalizing world. Global report on human settlements 2001. London: Earthscan Publications; 2001.

[20] On-line data services. International Energy Agency. 〈http://data.iea.org/ieastore/default.asp〉 [accessed December 2012].

[21] Riahi K, Roehrl RA. Energy technology strategies for carbon dioxide mitigation and sustainable development. Environ Econ Policy Stud 2000;3(2):89–124.

[22] Riahi K, Roehrl RA. Greenhouse gas emissions in a dynamics-as-usual scenarios of economic and energy development. Technol Forecast Soc Change 2000;63:175–206.

[23] Riahi Keywan, Frank Dentener, Dolf Gielen, Arnulf Grubler, Jessica Jewell, Zbigniew Klimont, et al. 2012. "Chapter 17 – energy pathways for sustainable development. In: Global energy assessment – toward a sustainable future. Cambridge, UK and New York, NY, USA: Cambridge University Press; Laxenburg, Austria: International Institute for Applied Systems Analysis. p. 1203–1306. 〈www.globalenergyassessment.org〉.

[24] 〈http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html〉.

[25] IPCC. Climate change 2007: mitigation of climate change. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, editors. Contribution of the working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press; 2007. p. 851.

[26] Ürge-Vorsatz D, Miladinova G, Paizs L. Energy in transition: From the iron curtain to the European Union. Energy Policy 2006;34(15):2279–97.

[27] Yu E, Liu J. Environmental impacts of divorce. PNAS 2007;104(51):20629–34.